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Design criteria for dynamic performance of a suspended structure for competition grade tennis courts

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ABSTRACT

The redevelopment of the Melbourne Park Tennis Centre incorporates something not previously seen at the home of a "Grand Slam" tournament – courts on the roof of a carpark building. To determine an appropriate structural design criterion for the suspended slabs, a study was undertaken on how vibrations induced by the players and external sources would be perceived. Following testing on existing courts and undertaking real time studies on forces exerted by tennis players, a series of criteria for acceptable vibrations in the structure was developed. The structure has now been successfully used during the 2013 and 2014 Australian Open tournaments.

Introduction

The Eastern Plaza and National Tennis Centre are part of the Melbourne Park Redevelopment project which is being managed by Major Projects Victoria for Sport and Recreation Victoria, the Melbourne and Olympic Parks and Tennis Australia. The recently completed Eastern Plaza project incorporates world-class tennis courts on the roof of the new carpark building. The new tennis courts are both indoor and outdoor, with the indoor courts covered by a metal and glass-clad architectural envelop as shown in the image above. Constructing international standard courts on top of a building is something not previously seen at the home of a "Grand Slam" tournament. This presented the design team with a new challenge – to determine an appropriate structural design criterion for the suspended slabs. The "stiffness" of the structure needed to be considered, in particular how vibrations induced by the players and external sources would be perceived. Following testing on existing courts and undertaking real time studies on forces exerted by tennis players, a design criteria for acceptable vibrations was developed for the suspended structure supporting the tennis courts.

This paper is not a "cook book" on how to design international standard competition courts on a suspended structure, as each case will vary. However it does provide guidance on the main parameters that should be considered, and describes the design approach that was successfully applied at the Melbourne Park venue.

Background

Most tennis courts suitable for international competition are located at ground level, on stable loadbearing layers supported by the ground. The structural design methodology for these courts is reasonably well understood within the

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structural engineering fraternity. However site constraints within the Melbourne Park complex dictated that for the new Eastern Plaza extension, opened just prior to the 2013 Australian Open, eight inside warm up courts and six outside courts needed to be located over the 1000 car carpark building. The Eastern Plaza extension also includes a player's gymnasium, a running track, and associated facilities which the design team identified could induce vibrations in the structure.

A study of major tennis venues around the world did not identify any design precedents for suspended "international standard" courts, so a design approach needed to be developed. The main concern was structure-borne vibrations, i.e. whether the movement of players or other external sources would cause unacceptable levels of vibration.

Structure-borne vibrations can be initiated from a number of sources. The simplest form of initiator is a single strike. Once struck, the structure will oscillate at its fundamental frequency or natural frequency. The length of time over which it will oscillate and the rate at which energy dissipates is a function of the inherent damping of the structure, which is influenced by the fixtures, services and furnishings attached to the structure, and the original form of the structure.

At the other end of the spectrum is the case where a cyclical load induces what could be considered a regular series of strikes on the structure. The effect of this type of loading is very dependent on the frequency of this cyclical load. If the load frequency does not match the natural frequency of the structure, then the resultant vibrations may not be significant. However when the load frequency matches the structure's natural frequency (or an integer multiple of the natural frequency), then significant vibrations can be induced.

In reality a tennis slab structure would be subjected to a wide range of forces, from single strikes generated by players jumping; a series of rhythmic strikes from players running; forces randomly generated from the movement of weights in the gymnasium; transient forces from cars moving around in the carpark or trains passing Melbourne Park on the nearby rail lines; and continuous forces from machinery in plantrooms. Each of these cases needed to be investigated.

Whilst the study of structure-borne vibrations can become quite technical, it was the desire of the client group (in particular Major Projects Victoria and Tennis Australia) that a quantifiable design approach be developed, so that this may be able to be used on similar future projects.

General principles of dynamics

Under the influence of an applied load, or series of loads, a series of vibrations will be induced in the structure. One of the simplest forms of an oscillating element is a guitar string. Once plucked, it will vibrate back and forth at its "natural frequency". At the moment just before it is released it has its maximum displacement and zero acceleration. Once released it will quickly return to its "at-rest" position, at which time its velocity would have accelerated to its maximum and its displacement will be zero. Momentum will drive the string beyond the at-rest position but it will decelerate until the moment it reaches its maximum negative displacement, at which time its acceleration will again be zero. As the string will be affected by friction from the air around it, and there will be some stretch in the string itself, there is an amount of "damping" in this system. The string will continue oscillating for some time, although the damping will ensure that in every cycle the displacement is slightly less than the previous, such that it will eventually cease. A structure however, is significantly more complex than a guitar string. It will generally consist of slabs, beams, columns and foundations, all of which can influence the frequency of the structure. Instead of having one natural frequency, as is the case of the guitar string, a structure can have a number of resonant frequencies (frequencies at which parts of the structure will resonate).

The main design parameter associated with an investigation into structure-borne vibration is usually the resultant acceleration. A person standing on the vibrating structure will feel this vibration. What they are actually sensing is the cycles of accelerations and decelerations. Remember that whilst sitting in a car travelling at a constant velocity we do not generally sense the motion. It is the accelerating force and the braking force (deceleration) that we feel. Interestingly, some people are more sensitive to the oscillating motion than others, and some people are more tolerant of this motion than others (and this may even change depending on the player's temperament).

Whilst the behaviour of the oscillation of a floor system can be quite complex, in simple terms under an applied striking force the following will occur:

- The structure will vibrate at its "natural frequency" or one of its resonant frequencies
- The length of time over which it will oscillate is a function of the magnitude of the force and the damping in the building
- People will sense the acceleration of the slab caused by the vibration

There are various ways to measure and report accelerations, the relevance of which is dependent upon the type of floor and the predominant forcing loads. In this instance, it was determined that the as the forcing load during play was a single strike, the most important structural response parameter is the peak acceleration induced in the structure.

A significant body of research has been undertaken over many years studying the perceptions of vibrations, particularly in North America based on work by Thomas Murray and David Allen. Much of this work has been published over a 30+ year period, and has formed the basis of the National Buildings Code of Canada's design criteria [1] and the American Institute of Steel Construction's Design Guide No. 11 [2]. These studies have identified that humans are most susceptible to vibrations in the range of 4–8 Hz. This means we are less concerned with vibrations that occur less than 4 times per second or more than 8 times per second. It was also identified that people are more tolerant of vibrations in structures such as footbridges and shopping centres (where they only have limited exposure to the vibration) but are less tolerant of vibrations in an office environment and even less tolerant in their home. The following chart (Fig. 1) is well known within the engineering fraternity as the basis for acceptable vibrations in different building types, based on the works of Murray and Allen.

A significant observation from these curves is that, above approximately 8 Hz, the allowable accelerations can increase. This is due in part to the fact that people are less susceptible to higher frequency vibrations, but also recognizes that as the frequency increases, the displacement associated with the oscillation will be less (for a similar applied force).

In addition to the works by Murray and Allen, other structure-borne vibration studies have been undertaken in Australia and internationally over many years on buildings such as hospital wards, operating theatres and the like. These have been referenced in the development of the criteria for the Eastern Plaza tennis courts.

Another critical factor in the development of the criteria for the tennis courts is the fact that a person using their own body weight to cause the load (by jumping, lunging, running etc) is generally not able to sense the resultant vibrations in a normal structure. This observation was central to the decision on where the accelerations should be measured in the structure, and is discussed in more detail below.

As is the norm for structures, the accelerations in the design curves above are expressed as a percentage of the acceleration due to gravity ($g = 9.8\ \text{m/s}^2$).

Load testing

At the pre-tender stage of the Eastern Plaza project Major Projects Victoria and Tennis Australia recognised that this was an unusual project requiring additional inputs, so Tennis Australia commissioned testing to examine the dynamic performance of selected existing tennis courts. One court tested was the existing Margaret Court Arena, which has been used for many years during previous Australian Open Grand Slam tournaments, and consists of a post-tensioned slab-on-grade. The second test was on a tennis court located on a carpark building associated with a major hotel development. In addition, to accumulate more data for comparison a third series of tests were undertaken on a tennis court located on a suspended slab at a tennis facility in Auckland New Zealand during the final design stage. Measurements of accelerations and frequencies were taken at each of the facilities during a tennis match. As was expected, the dynamic response measured from these three tennis courts differed greatly. It was determined that for the Melbourne Park facility, the new suspended courts needed to be stiffer than the two suspended courts tested.

In addition, Major Projects Victoria and Tennis Australia also commissioned some actual impact load tests, undertaken at the Victoria Institute of Sport (VIS) Sports Science Department. A competition player was put through a series of typical tennis manoeuvres over a load cell. The actual forces exerted on to the floor from these manoeuvres were measured against time. Selected graphical outputs of these tests follow. The testing showed that under a "jump smash" action, the force exerted on the floor was equivalent to approximately 12.5 times the player's weight, but only for a short period of time. Under actions such as running and changing directions, the Gross Reaction Force (GRF) is approximately 2 times body weight, but occurs over a longer time and is obviously likely to occur much more frequently during a match. Under a serve

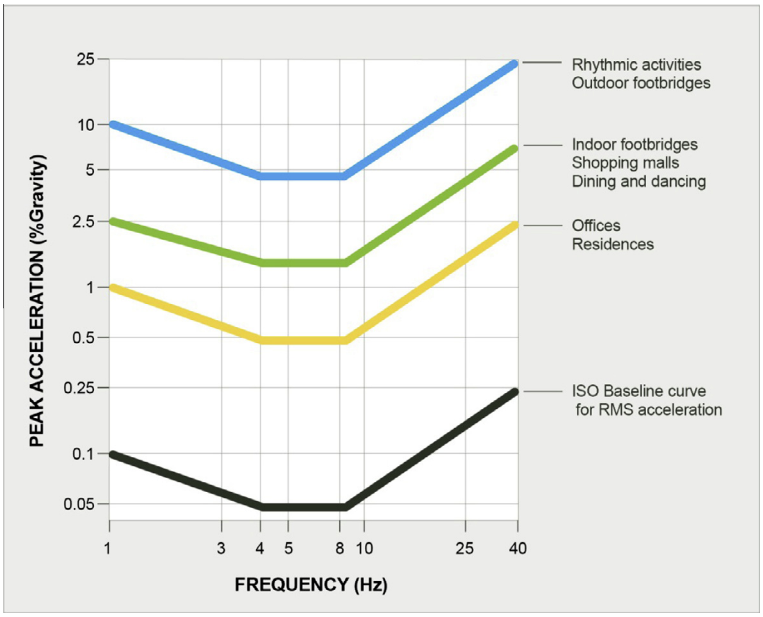

Fig. 1. Acceleration Design Curves based on the works of Murray and Allen. (Adapted from American Institute of Steel Construction Design Guide No. 11, AISC 1997.)

motion, the maximum GRF was approximately 2.5 times the body weight, increasing to approximately 3.2 times under a volley motion (Figs. 2 and 3).

The results of the Volley tests were of particular interest, as this represents an activity that would occur relatively frequently during a match, and produces a GRF plot with a peak similar to a "Heel Drop". A Heel Drop test is a universally accepted (albeit crude) test to study vibrations in structures. It is performed by a person of approximately 80 kg standing on their toes with their heels approximately 50 mm above the surface, dropping their heels to the surface whilst keeping their legs stiff. It was identified that a Heel Drop test could be used to simulate the Volley design case, and could be reproduced with reasonable consistently.

Development of a criteria

To design a structure with "imperceptible" accelerations under all load conditions was virtually impossible and, at best, extremely cost-prohibitive. It was accepted that a design criteria had to be developed. Rather than try to adopt a single criterion for the design of the structure, it was decided that a rational approach coupling the probability of a load occurrence with an appropriate allowable acceleration was more logical. The Jump Smash action was identified as the most severe of the design cases, however this activity is expected to occur less frequently than serving, volleying and significantly less than running/changing directions. In addition to these forces caused by the players, we also needed to consider structure-borne vibrations caused by vehicles in the carpark, trains and trams passing the facilities, activities in the gymnasium, and machinery in the plantrooms of the facility.

Given that the professional players normally play on "on grade" courts that experience minimal accelerations under impacts, it was deemed necessary that a tight criteria for the suspended slabs was necessary. The starting point was to consider a criterion for the most common forms of activity – running and changing directions during a match. Australian Standard AS2670.1 – 2001 [3], which is based on ISO 2631-1:1997, indicates that approximately 25% of alert fit persons cannot detect a vertical vibration with a peak magnitude of 0.2%g. Similarly, the Department of Environment and Conservation NSW's "Assessing Vibration: A Technical Guideline" [4] provides a maximum recommended acceleration from a vertical continuous vibration source in a hospital operating theatre which equates to a peak acceleration of approximately 0.14%g. Anecdotal evidence from the design team on the National Tennis Centre was that a figure of 0.2%g had recently been used as the design criterion for a large Australian hospital. It was therefore decided that the criterion where the peak accelerations is limited to less than 0.2%g (for structures in the range of 4–8 Hz) would be appropriate, as it was deemed that even the most temperamental tennis player would agree that if a surface was stiff enough to for a doctor to operate, it would be acceptable for a tennis match. Following the precedent of the curves as shown above, the allowable acceleration could increase if a stiffer structure (with a higher natural frequency) was provided.

The "background" vibrations from external sources (vehicles, trains, trams, activities in the gym, mechanical plant etc.) was the second criterion to be determined. As this vibration could be expected to occur for extended periods of time, an acceleration limit less than the running/changing direction criterion was deemed appropriate. Following an assessment of what could be realistically and economically achieved in design, an acceleration curve at 80% of the running/changing direction criteria was adopted. This is nearing the level at which many people would consider is imperceptible.

The next criterion to be considered was for the serve action and volley action. As this activity would occur less frequently than the running and changing direction, a higher acceleration was considered acceptable. A peak acceleration of 0.5%g was

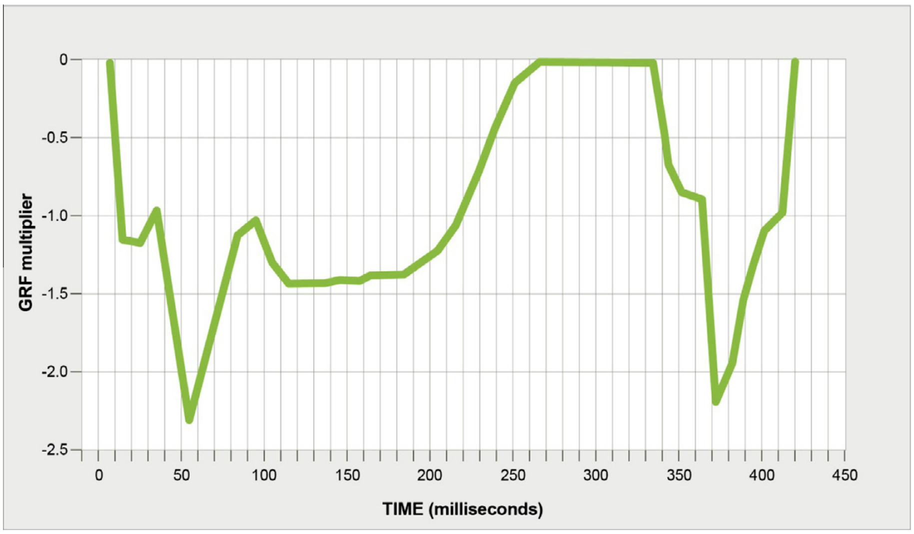

Fig. 2. Gross reaction force diagram for change in direction.

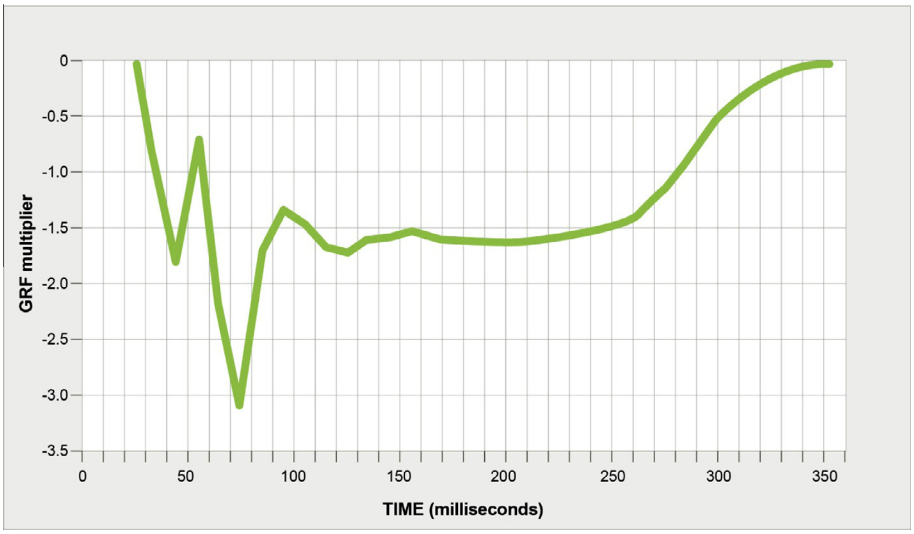

Fig. 3. Gross reaction force diagram for volley.

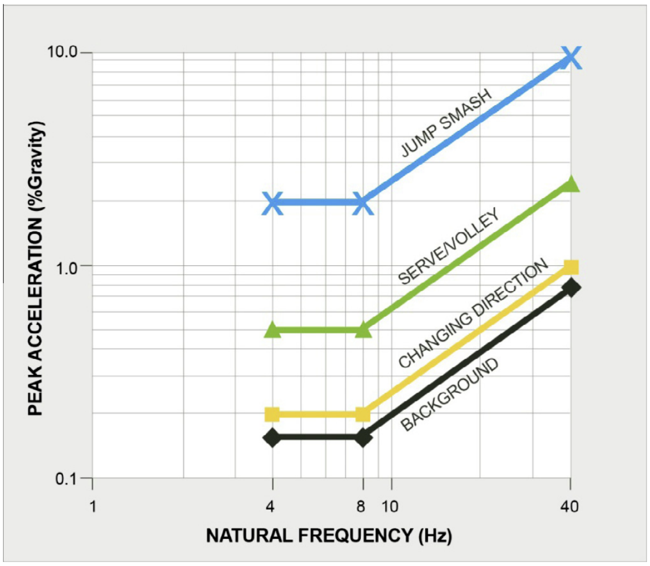

Fig. 4. Adopted design criteria.

adopted, increasing in line with the curves shown above for frequencies greater than 8 Hz. This is similar to what would be deemed acceptable in an office or residential environment, as shown in Fig. 1. A convenient aspect of this criterion is that the Gross Reaction Force generated from the players is similar in magnitude and duration to a heel drop test, which is relatively easy to replicate by technicians.

Under the jump smash action a more lenient criteria was necessary, as a cost-prohibitive structure would otherwise be necessary. Through consultation with Marshall Day Acoustics, it was agreed that as the duration of the significant force was extremely short, an allowable acceleration of 2%g (increasing for structures above 8 Hz) would be acceptable. The resultant design curves are presented in Fig. 4 below.

Location of acceleration measurements

The location of the acceleration measurements on the structure is another important feature of the adopted design criteria. For the bottom-most curve, (the background vibrations), these accelerations should not be exceeded anywhere on the slab. For the remainder of the criteria, however, two different practical factors were considered. As noted previously, it is

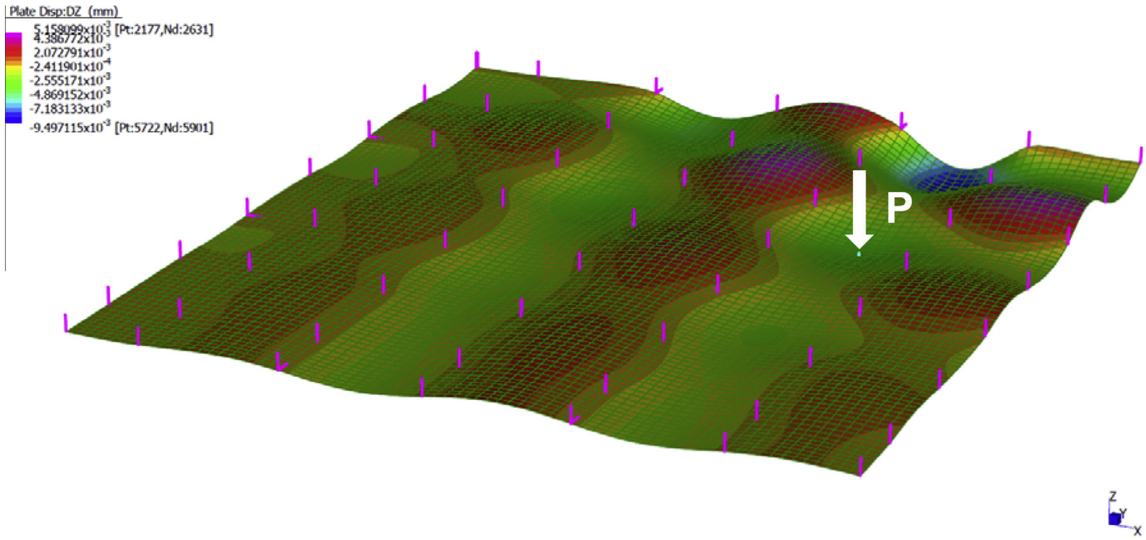

Fig. 5. Screen shot of the Aurecon Strand 7 model displacement under dynamic load (Load exerted at "P". Magenta lines represent supports below). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

known that the person performing the forcing action does not feel the resulting accelerations. In a tennis match environment it is therefore typically the umpire or a doubles partner that is likely to be located within about 4 m of that player.

It was also known that the structure, to have requisite stiffness to accommodate the design criteria, would likely have columns and/or beams on a grid of around 8–10 m. By undertaking a preliminary 3D Finite Element Analysis (FEA) and studying the modeshapes of the resonant frequencies of the likely structural system, it was known that maximum and minimum accelerations are likely to occur at multiples of grids and half-grids of the structure. The selected criteria was therefore to place the forcing load at the most severe location on the structure as determined by the FEA analyses. Accelerations were then checked at a maximum of 5 m centres in all directions (but coinciding with the grids and half-grids of the structure). Due to the length of a tennis court (and the fact that the players may be both located beyond the baseline) it was considered necessary to continue the measurements for a distance of approximately 25–30 m.

Pre-construction dynamic analysis

Significant analysis of the structure is required prior to construction, to determine the dimensions of structure to be constructed to meet the design criteria. A full 3D finite element analysis (FEA) with time history capability is necessary to model the characteristics of the load (from the GRF plots) and the response of the structure at multiple locations. To model the structure's response, an accurate assessment of the effective Moment of Inertia of the structural elements is essential. All flexural concrete members form fine cracks in the tensile zones which reduce its stiffness at these locations and increase deflections. These micro-cracks result in a varying effective Moment of Inertia across the structure, which needs to be accurately modelled before a realistic FEA can be undertaken. Similarly, under dynamic loads it is appropriate to use a higher Young's Modulus for the structural elements than what would normally be used for a static analysis.

The design of the floor structure was undertaken by the structural consultant for the builder, however to test the accuracy of their model, Aurecon produced our own Strand 7 FEA model. This reflected the edge conditions between the movement joints in the structure and the properties of the supporting columns below. Based on the layout of the courts and the structural grids, it was identified that the maximum accelerations in the applicable portions of the building could be generated in the structure by locating the forcing load in the bay as shown in Fig. 5. The structure was then designed and detailed based on this pre-construction dynamic analysis.

From the FEA analysis, a design will evolve to satisfy the vibration criteria. The resultant structure is likely to be considerably stiffer than a "normal" slab that would otherwise be required for an office or retail development based on the same column grid.

The net result of the complexity of the dynamics issue is that a structure of this type could easily take the designer at least ten times the effort to design, and will cost at least double the cost to construct, when compared to a normal slab of similar spans. Further allowances should then be made for testing post-construction.

Post construction testing

Once the structure had been completed, a series of tests were undertaken to measure the accelerations produced at the critical point located in Fig. 5. Tests were done whilst a player ran, changed direction, served, volleyed and hit jump smashes, with accelerometers at intervals up to 28 m away from the strike point. Tests were also performed using dropped loads, which were considered to more accurately reproduce the specified design GRF's in a repeatable manner. In addition, Heel Drop tests were undertaken to simulate the volley action. The results of the measured resonant frequencies of the structure were found to be lower than predicted, although the resulting accelerations were still found to be within the criteria set for the project, as shown in Fig. 4.

As the Eastern Plaza was opened prior to the end of 2012, it was used for the first time during the 2013 Australian Open, and again during the recent 2014 Australian Open. Feedback from the players and Tennis Australia was that the facility has performed well and met their expectations.

Summary

The redevelopment of the Melbourne Park Tennis Centre incorporates courts on the roof of the new carpark building. Constructing international standard courts on top of a building is something not previously seen at the home of a "Grand Slam" tournament. This presented the design team with the challenge of how to determine an appropriate structural design criterion for the response of the structure to vibrations induced by the players and external sources.

Tests on existing courts were undertaken, as well as real time studies on forces exerted by tennis players. Based on a rational approach, relating how often an event may occur to an appropriate acceleration limit, a series of design curves was developed for acceptable vibrations in the suspended structure supporting the tennis courts. A criteria for the locations on the slab where the measurements should be taken was also determined.

This report provides guidance on the main parameters that should be considered, and the design approach that was applied for the dynamic performance of the suspended tennis courts at the Melbourne Park venue. The structure was successfully used during the 2013 and 2014 Australian Open tournaments.

Acknowledgments

The authors wish to acknowledge the contributions made during the development of the design criteria by Tennis Australia, Melbourne & Olympic Parks, Watson Moss Growcott, and Marshall Day Acoustics. We also acknowledge the inputs of Watpac Construction and the project structural engineer Winward Structures.

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